

APPARATUS AND METHODS FOR MONITORING AND CONTROLLING POWER AMPLIFIER LINEARITY USING DETECTED FUNDAMENTAL AND HARMONIC COMPONENTS

BACKGROUND OF THE INVENTION

The present invention relates to communications apparatus and methods, and more particularly, to power amplifier monitoring and control apparatus and methods.

5 Communications apparatus often include a power amplifier that is used to amplify a signal to appropriate levels for transmission, for example, in free space or on a transmission line. For example, wireless terminals (e.g., cellular telephones and other wireless-capable devices) typically include a power amplifier that is used to amplify a radio frequency (RF) signal for transmission by an antenna.

10 Power amplifiers often encounter non-ideal reflection arising from impedance mismatches between the power amplifier and transmission medium. In the case of a wireless terminal power amplifier, for example, impedance mismatches may be caused by a variety of factors, including changes in surroundings caused by motion of the terminal and/or objects in the terminal's environment. Such changes may occur,
15 for example, when the terminal is moved near a user's body or near reflective or shielding structures.

 Impedance mismatches can significantly affect performance of a power amplifier. For example, impedance mismatch may cause the voltage standing wave ratio (VSWR) presented to the power amplifier to be high enough to cause damaging
20 voltages and/or currents at the power amplifier's output. In addition, large reflected power and high VSWR may lead to performance-degrading phenomena, such as AM/AM and AM/PM distortion.

 Conventional solutions for avoiding or reducing such problems include reducing mismatch and/or reducing its damaging or degrading effects. In a wireless
25 terminal, for example, mismatch can be reduced by using an isolator or a balanced antenna circuit. Other conventional approaches attempt to detect when undesirable or

dangerous VSWR or reflected power conditions are present (or are about to be present), and take corrective and/or protective actions that can prevent damage or reduce performance degradation.

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SUMMARY OF THE INVENTION

In embodiments of the invention, an apparatus for monitoring a power amplifier coupled to a transmission medium includes a detector circuit, coupled to the transmission medium, that generates first and second detector signals corresponding to respective fundamental and harmonic components of a power amplifier output
10 signal produced by the power amplifier. A comparing circuit is coupled to the detector circuit and compares the first and second detector signals. The comparing circuit, responsive to a comparison of the first and second detector signals, may generate a signal that indicates linearity of the power amplifier.

In some embodiments of the invention, the detector circuit may generate the
15 second detector signal without requiring phase information for the harmonic component. For example, the detector circuit may include a directional coupler and a first power detector that generate the first detector signal. The second detector signal may be generated by a combination of a filter, in particular, a bandpass or high pass filter coupled to the transmission medium by a high impedance shunt circuit, and a
20 second power detector. Such a configuration may take advantage of a low pass filter coupled to the power amplifier's output, which reflects the harmonic component such that detection of the harmonic based on amplitude is substantially independent of impedance matching between the power amplifier and a load, such as an antenna.

In other embodiments of the invention, the detector circuit includes a first
25 directional coupler that couples a power amplifier to the antenna and that generates a first output signal responsive to the power amplifier output signal. A first power detector is coupled to the first directional coupler and generates a first detector signal corresponding to a fundamental component of a power amplifier output signal from the first output signal. The detector circuit further includes a second directional
30 coupler that couples the power amplifier to the antenna and that generates a second

output signal. A second power detector, coupled to the second directional coupler, generates a second detector signal corresponding to a harmonic component of the power amplifier output signal from the second output signal. The first output signal may correspond to a forward fundamental component, and the second output signal may correspond to a reflected harmonic component. The second directional coupler may be a dual-band coupler that may also detect a reflected fundamental component.

According to other embodiments of the invention, an apparatus includes an antenna and a power amplifier that generates a power amplifier output signal in a transmission medium coupling the power amplifier to the antenna. A detector circuit, coupled to the transmission medium, generates first and second detector signals corresponding to respective fundamental and harmonic components of the power amplifier output signal. A control circuit, coupled to the detector circuit and operatively associated with the power amplifier, controls the power amplifier responsive to a comparison of the first and second detector signals. In particular, the control circuit may control linearity of the power amplifier responsive to a comparison of the first and second detector signals, for example, by controlling the level of an input signal applied to the power amplifier and/or DC bias of the power amplifier. The detector circuit may include various combinations of directional couplers and filter circuits as described above.

According to method embodiments of the invention, first and second detector signals corresponding to respective fundamental and harmonic components of a power amplifier output signal are generated. The first and second detector signals are compared to determine linearity of the power amplifier. The power amplifier linearity may be controlled responsive to the comparison of the first and second detector signals, for example, by controlling input signal level and/or DC bias.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1-4 are schematic block diagrams illustrating power amplifier monitoring apparatus and operations according to embodiments of the invention.

FIGs. 5-8 are schematic block diagrams illustrating power amplifier control apparatus and operations according to embodiments of the invention.

FIG. 9 is a schematic diagram illustrating a power detection circuit according to embodiments of the invention.

FIG. 10 is a schematic diagram illustrating a power comparison circuit according to embodiments of the invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which illustrative embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. As will be appreciated by those of skill in the art, the present invention may be embodied as methods or apparatus.

For power amplifier applications in which an input signal having a desired, fundamental frequency is applied to a power amplifier, non-linear operation (e.g., saturation or clipping) of the amplifier can be detected by comparison of fundamental and harmonic components of the output signal produced by the amplifier. These fundamental and harmonic components can be detected in ways that take advantage of components, such as directional couplers and output filters, typically used in wireless or other transmitters for purposes other than power amplifier linearity detection, as will be described for various embodiments of the invention herein.

FIG. 1 illustrates a power amplifier monitoring apparatus 100 according to embodiments of the invention. A power amplifier 10 generates an output signal 11 (e.g., a radio frequency (RF) signal) on a transmission line 20. The monitoring apparatus 100 includes a detector circuit 110, here shown as including first and second detectors 112, 114. The first detector 112 generates a first detector signal 113

corresponding to a fundamental component of the power amplifier output signal **11**. The second detector **114** generates a second detector signal **115** that corresponds to a harmonic component of the power amplifier output signal **11**. The monitoring apparatus **100** further includes a comparing circuit **120** that compares the first and second detector signals **113**, **115**, and generates a power amplifier linearity indicating signal **125** based on the comparison.

The linearity indicating signal **125** is generated based on a comparison of the first and second detector signals **113**, **115**. For example, the first and second detector signals **113**, **115** may be analog signal power sense signals that are generated using diode-type power detection circuits, such as the detection circuit **930** discussed below with reference to FIG. 9. Such signals may be compared using, for example, an analog comparison circuit, such as the comparison circuit **1000** discussed below with reference to FIG. 10.

It will also be appreciated that, generally, the detector circuit **110** and the comparing circuit **120** of the monitoring apparatus **100** may be implemented in a number of different forms. For example, the detector circuit **100** may utilize analog and/or digital circuitry to implement the functions of the detectors **112**, **114**, such as frequency selective couplers and analog filters that detect selected components of the power amplifier output signal **11**, and analog power detectors that determine respective power levels of the passed components. Some of these functions may alternatively be performed by analogous digital circuitry, such as by code executing on a data processor such as a microprocessor, microcontroller or digital signal processor (DSP).

Similarly, the comparing circuit **120** may be implemented in analog circuitry, digital circuitry, or combinations thereof. For example, if the detector signals **113**, **115** produced by the detector circuit **110** include respective analog voltages representing respective power levels of respective fundamental and harmonic components of the power amplifier output signal **11**, the comparing circuit **120** may include, for example, an analog comparator circuit or a similar circuit that compares the respective voltage levels and generates an output signal representative of the

comparison. It will be appreciated, however, that other comparison techniques may also be used.

FIG. 2 illustrates an exemplary implementation of a power amplifier monitoring apparatus **200** according to embodiments of the invention. As in FIG. 1, a power amplifier **10** generates an output signal **11** on a transmission line **20**, here shown as connected to a low pass filter **30** and an antenna **40**. The power amplifier monitoring apparatus **200** includes a detector circuit **210** coupled to the transmission line **20**. The detector circuit **210** includes a directional coupler **211** coupled to a first power detector **214a**. In combination, the directional coupler **211** and the first power detector **214a** generate a first detector signal **215a** representing power of a forward fundamental component of the power amplifier output signal **11**.

The detector circuit **210** further includes first, second, and third bandpass filters **213a**, **213b**, **213c**, that are capacitively coupled to the transmission line **20** by a high-impedance capacitive shunt circuit **212**. The bandpass filters **213a**, **213b**, **213c** may be designed to respective harmonics of the fundamental frequency of the power amplifier output signal **11**. In combination with respective second, third and fourth power detectors **214b**, **214c**, **214d**, the respective bandpass filters **213a**, **213b**, **213c** generate respective second, third, and fourth detector signals **215b**, **215c**, **215d** representing respective power levels of respective harmonic components of the power amplifier output signal **11**. The detector signal **215a** for the forward fundamental component is compared with the detector signals **215b**, **215c**, **215d** for the harmonic components in a comparing circuit **220**, which generates a linearity indicating signal **225** based on the comparison.

It will be understood that the detector circuit **210** and comparing circuit **220** of the monitoring apparatus **200** may be implemented using a variety of different components. For example, the power detectors **214a**, **214b**, **214c** may include discrete RF diode detector circuits and/or integrated circuit devices that provide similar functionality. As will be appreciated by those skilled in the art, such detector circuits may produce an analog and/or a digital output signal representative of the

power detected by the detector circuit **210**. Accordingly, the comparing circuit **220** may include analog and/or digital circuitry appropriate for processing such signals.

The monitoring apparatus **200** can take advantage of elements that are typically found in a wireless terminal or other device, but are conventionally used for other purposes. In particular, a directional coupler and associated power detector, such as the directional coupler **211** and the first power detector **214a**, may be used in a wireless terminal to perform conventional power control functions, such as output power and VSWR control. Accordingly, generation of the first detector signal **215a** may not require additional hardware.

The shunt circuit **212** and filters **213a**, **213b**, **213c** can take advantage of the presence of the output filter **30** to simplify detection of harmonics. In particular, a potential problem in determining power levels for a harmonic is accounting for changes in relative amplitudes of forward and reflected harmonic waves arising from changes in impedance on the transmission line **20**. The low pass filter **30**, which is typically designed to preferentially pass the fundamental component of the power amplifier output signal **11**, may reflect the harmonic such that detection of the harmonic power based on amplitude information is substantially independent of antenna matching. This allows the use of shunt elements, such as the shunt circuit **312** and filters **313a**, **313b**, **313c**, which can provide potentially less loss than might be experienced if additional series elements are used.

FIG. 3 illustrates an alternative configuration for a power amplifier monitoring apparatus **300** according to other embodiments of the invention. The power amplifier **10**, transmission line **20**, low pass filter **30** and antenna **40** are as described above with reference to FIG. 2. The monitoring apparatus **300** includes a detector circuit **310** coupled to the transmission line **20** and operatively associated with a comparing circuit **320**. The detector circuit **310** includes a forward directional coupler **311** coupled to a first power detector **314a**, which produces a first detector signal **315a** representing power of a forward fundamental component of a power amplifier output signal **11**. A second, dual-band directional coupler **312** has a first output coupled to a second power detector **314b**, which generates a second detector signal **315b** that

represents power of a reflected fundamental component of the power amplifier output signal **11**.

The second directional coupler **312** also has a second output coupled to a bank of bandpass filters **313a**, **313b**, **313c**. Respective ones of the bandpass filters **313a**, **313b**, **313c** pass respective selected harmonics of the fundamental of the power amplifier output signal **11**. Respective ones of the band pass filters **313a**, **313b**, **313c** are coupled to respective ones of third, fourth and fifth power detectors **314c**, **314d**, **314e**, which generate respective third, fourth and fifth detector signals **315c**, **315d**, **315e** representing respective power levels of the selected harmonics. The third, fourth and fifth detector signals **315c**, **315d**, **315e**, representing the harmonic power levels, and the first detector signal **315a**, representing the forward fundamental power, are compared by the comparing circuit **320** to generate a linearity indicating signal **325**. As shown, the first and second detector signals **315a**, **315b** may also be passed on to a circuit **50** that detects VSWR and/or reflected power.

FIG. 4 illustrates yet another alternative configuration for a power amplifier monitoring apparatus **400** according to other embodiments of the invention. The power amplifier **10**, transmission line **20**, low pass filter **30** and antenna **40** are as described above with reference to FIG. 2. The monitoring apparatus **400** includes a detector circuit **410** coupled to the transmission line **20** and operatively associated with a comparing circuit **420**. The detector circuit **410** includes a forward directional coupler **411** coupled to a first power detector **414a**, which produces a first detector signal **415a** representing power of a forward fundamental component of a power amplifier output signal **11**. A second, dual-band directional coupler **412** has a first output coupled to a second power detector **414b**, which generates a second detector signal **415b** that represents power of a reflected fundamental component of the power amplifier output signal **11**.

The second directional coupler **412** also has a second output coupled to a high pass filter **413**. The high-pass filter **413** passes one or more selected harmonics of the fundamental. The high pass filter **413** is coupled to a broadband power detector **414c**, which generates a third detector signal **415c** representing an aggregate power level of

the selected harmonic(s). The third detector signal **415c** and the first detector signal **415a** are compared by the comparing circuit **420** to generate a linearity indicating signal **425**. As shown, the first and second detector signals **415a**, **415b** may also be passed on to a circuit **50** that detects VSWR and/or reflected power.

5 FIG. 5 illustrates other embodiments of the present invention. A signal processing circuit **510**, including a power amplifier **512**, generates an output signal **11** on a transmission line **20**. The signal processing circuit **510** is responsive to a control input **535** to adjust the linearity of the power amplifier **512**, for example, to change the DC bias if the power amplifier **512** and/or the input signal level presented to the
10 power amplifier **512**. A detector circuit **520** is coupled to the transmission line **20**, and includes first and second detectors **522**, **524** that generate respective first and second detector signals **523**, **525** corresponding to respective fundamental and harmonic components of the power amplifier output signal **11**. A control circuit **530** is responsive to the first and second detector signals **523**, **525** and generates the
15 control input **535** based on a comparison of the first and second detector signals **523**, **525**.

 According to other embodiments of the invention illustrated in FIG. 6, a power amplifier **610** receives an input signal **631** from a variable gain circuit **636** of a control circuit **630** and, responsively thereto, generates an output signal **11** on a transmission
20 line **20** coupled to a low pass filter **30** and antenna **40**. The power amplifier **610** operates with a DC bias controlled by a bias control signal **633** applied by a processor **634** in the control circuit **630**. A detector circuit **620** is coupled to the transmission line **20**, and includes a first and second directional couplers **621a**, **621b** coupled to respective first and second power detectors **624a**, **624b**. The first and second power
25 detectors **624a**, **624b** generate respective first and second detector signals **625a**, **625b** representing respective forward and reflected fundamental power levels of the power amplifier output signal **11**.

 The detector circuit **620** further includes first, second and third bandpass filters **623a**, **623b**, **623c** coupled to the transmission line **20** by a shunt circuit **622**.
30 Responsive to the bandpass filters **623a**, **623b**, **623c**, third, fourth, and fifth power

detectors **624c**, **624d**, **624e** generate third, fourth and fifth detector signals **625c**, **625d**, **625e** that represent respective power levels of respective harmonic components of the power amplifier output signal **11**.

5 The control circuit **630** further includes first, second, third, fourth, and fifth analog to digital (A/D) converters **632a**, **632b**, **632c**, **632d**, **632e** that receive respective ones of the detector signals **625a**, **625b**, **625c**, **625d**, **625e**, and generate digital values therefrom representing respective measured power levels for the fundamental and harmonic components. These digital values are passed on to the processor **634**, which generates a level control signal **635** for the variable gain circuit **636** and the bias control signal **633** based on a comparison of the digital values.

10 It will be appreciated that the detector circuit **620** and the control circuit **630** of FIG. 6 may be implemented in a number of different ways. For example, the processor **634** may include a microcontroller, microcomputer, digital signal processor or similar computing device, which may implement other computing or signal processing operations in addition to the comparing and control operations described above. The variable gain circuit **636** may, for example, be a variable gain amplifier or similar device in an RF signal path, or may be integrated into other signal processing apparatus, such as a modulator, that can vary the level of the input signal **631** applied to the power amplifier **610**.

20 An implementation as might be used in a wireless terminal according to embodiments of the invention is illustrated in FIG. 7. A power amplifier **710** receives an input signal **731** (e.g., an RF carrier modulated signal) from a modulator **736** in a control circuit **730**. The modulator **736** generates the input signal **731** responsive to a data signal **739** generated by a baseband processor **734** of the control circuit **730**, with a level that is controlled responsive to a level control signal **735**. Responsive to the input signal **731**, the power amplifier **710** generates an output signal **11** on a transmission line **20** coupled to a low pass filter **30** and antenna **40**. The power amplifier **710** operates with a DC bias controlled by a bias control signal **733** applied by the baseband processor **734**.

A detector circuit **720** is coupled to the transmission line **20**, and includes a first and second directional couplers **721a**, **721b** coupled to respective first and second power detectors **724a**, **724b**. The first and second power detectors **724a**, **724b** generate respective first and second detector signals **725a**, **725b** representing
5 respective forward and reflected fundamental power levels of the power amplifier output signal **11**. The detector circuit **720** further includes first, second and third bandpass filters **723a**, **723b**, **723c** coupled to the transmission line **20** by a shunt circuit **722**. Responsive to the bandpass filters **723a**, **723b**, **723c**, third, fourth, and fifth power detectors **724c**, **724d**, **724e** generate third, fourth and fifth detector signals
10 **725c**, **725d**, **725e** that represent respective power levels of respective harmonic components of the power amplifier output signal **11**.

The control circuit **730** also includes first, second, third, fourth, and fifth analog to digital (A/D) converters **732a**, **732b**, **732c**, **732d**, **732e** that receive
15 respective ones of the detector signals **725a**, **725b**, **725c**, **725d**, **725e**, and generate digital values therefrom representing respective measured power levels for the fundamental and harmonic components. These digital values are passed on to the baseband processor **734**, which generates the level control signal **735** and the bias control signal **733** based on a comparison of the fundamental and harmonic power levels represented by the digital values.

Other embodiments of the invention are illustrated in FIG. 8. A power
20 amplifier **810** receives an input signal **831** from a variable gain amplifier **832** of a control circuit **830**. The variable gain amplifier **832** generates the input signal **831** responsive to a carrier-modulated signal **839** generated by, for example, a modulator (not shown), at a gain that is controlled responsive to a level control signal **835**.
25 Responsive to the input signal **831**, the power amplifier **810** generates an output signal **11** on a transmission line **20** coupled to a low pass filter **30** and antenna **40**. The power amplifier **810** operates with a DC bias controlled by a bias control signal **833** applied by the bias control circuit **834** included in the control circuit **830**.

A detector circuit **820** is coupled to the transmission line **20**, and includes a
30 first and second directional couplers **821a**, **821b** coupled to respective first and

second power detectors **824a**, **824b**. The first and second power detectors **824a**, **824b** generate respective first and second detector signals **825a**, **825b** representing respective forward and reflected fundamental power levels of the power amplifier output signal **11**. The detector circuit **820** further includes first, second and third
5 bandpass filters **823a**, **823b**, **823c** coupled to the transmission line **20** by a shunt circuit **822**. Responsive to the outputs of the bandpass filters **823a**, **823b**, **823c**, third, fourth, and fifth power detectors **824c**, **824d**, **824e** generate third, fourth and fifth detector signals **825c**, **825d**, **825e** that represent respective power levels of respective harmonic components of the power amplifier output signal **11**. The control circuit
10 **830** receives the detector signals **825a**, **825b**, **825c**, **825d**, **825e**, and controls the variable gain amplifier **832** and the bias control circuit **834** responsive to a comparison of the detector signals **825a**, **825b**, **825c**, **825d**, **825e**.

It will be appreciated that the embodiments described with reference to FIGs. 7 and 8 are provided for illustrative purposes, and that a variety of other circuit
15 configurations fall within the scope of the invention. For example, instead of determining power for discrete, multiple harmonics as illustrated in FIGs. 7 and 8, power of a single harmonic or an aggregate of harmonics may be determined. In addition, instead of shunt-type harmonic detection, dual-band directional couplers (as described, for example, with reference to FIGs. 3 and 4) or other devices may be used
20 to detect harmonics. Techniques for controlling power amplifier linearity other than input signal level and bias may also be used.

FIG. 9 illustrates a power detection circuit **930**, in particular, an envelope-type power detection circuit, that may be used with the present invention. As shown, the power detection circuit **930** is coupled, along with a termination circuit **920**, to a
25 directional coupler **910**. The directional coupler **910** is also coupled to a transmission line **901**, e.g., a transmission line connecting a power amplifier to an antenna, and generates a signal that is applied to the power detection circuit **930** responsive to a signal present on the transmission line **901**. The power detection circuit **930** includes a diode pair **932** that produces a power second signal **935** that is biased and filtered by
30 first and second circuits **934**, **936**. In particular, the second circuit **936** may be

configured such that the power sense signal **935** represents a selected component, e.g., fundamental or harmonic, of a signal present on the transmission line **901**.

FIG. 10 illustrates an exemplary comparison circuit **1000** that compares respective power sense signals **1001a**, **1001b** for respective fundamental and harmonic components of a signal. The power sense signals **1001a**, **1001b** are threshold detected by respective threshold detector circuits **1010a**, **1010b** and amplified by respective variable gain amplifiers **1020a**, **1020b**. In conjunction with the threshold detector circuits **1010a**, **1010b**, the variable gain amplifiers **1020a**, **1020b** generate respective signals that have desired levels for comparison of the fundamental and harmonic components that are applied to a comparator circuit **1030**, e.g., an operational amplifier circuit configured to generate a signal **1005** indicative of the relative power levels of the fundamental and harmonic components represented by the power sense signals **1001a**, **1001b**. The signal **1005** may serve, for example, as an indication of linearity of a power amplifier that produces the fundamental and harmonic components, as described above with reference to FIG. 1.

It will be appreciated that the power detection circuit **930** of FIG. 9 and the comparison circuit **1000** of FIG. 10 are provided for exemplary purposes, and that a variety of other types of detector and comparison circuits may be used with the invention. It will be understood that, in general, such circuits may include analog and/or digital circuitry.

In the drawings and specification, there have been disclosed typical illustrative embodiments of the invention and, although specific terms are employed, they are used in a generic and descriptive sense only and not for purposes of limitation, the scope of the invention being set forth in the following claims.